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Constant–Temperature Anemometry Measurements in Hypersonic Boundary Layers

by

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One of the major unresolved issues in fluid dynamics is the nature of apparent stresses, called Reynolds stresses, which occur in turbulent boundary layers. In hypersonic boundary layers, the flow physics is further complicated by the large temperature and density fluctuations and the concomitant contamination of the Reynolds stresses by "fictitious" terms. Because of the severe flow environment and the extraordinary demands on sensors and instruments, the turbulence characteristics of hypersonic boundary layers have been studied in only a cursory fashion. The plans for supersonic (HSCT) and hypersonic (NASP) vehicles have made supersonic flow physics one of the critical pacing technologies in aerospace science. In particular, experimental data is needed to verify candidate computer models and to reach an improved understanding of the turbulence physics. The research performed this summer at NASA–Langley's Experimental Flow Physics Branch is the start of a substantial effort to refine existing instrumentation and develop experimental techniques to measure the various components of the Reynolds stress in hypersonic boundary layers.

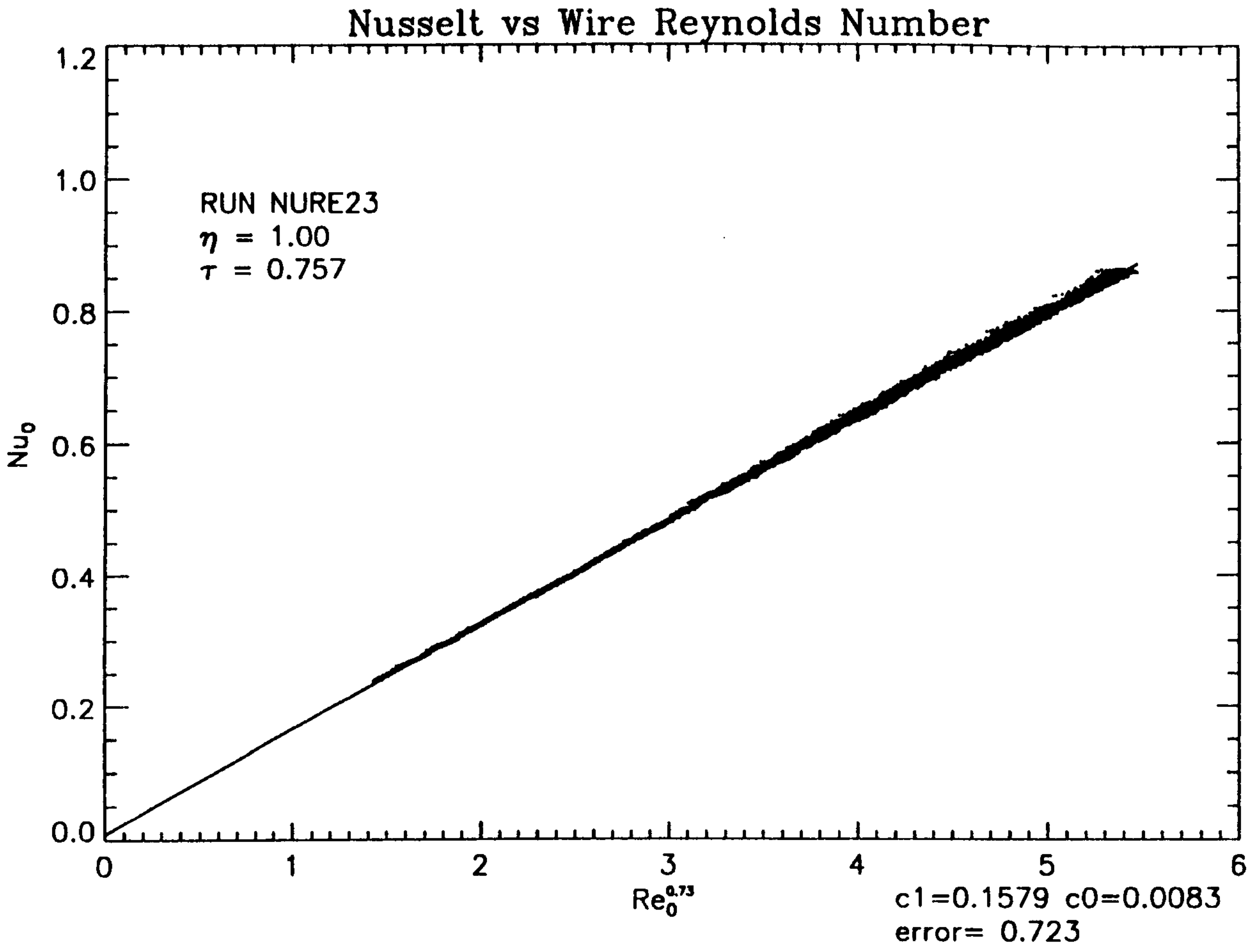
The few fluctuating velocity measurements which have been made in hypersonic boundary layers have been acquired using constant–current hot–wire anemometry (CCA). While CCA is able to separate contributions from various turbulence modes, it cannot be used to acquire instantaneous signals because it must be operated at several different overheat settings during the same run. Constant–temperature hot–wire anemometry (CTA) does not suffer from this shortcoming (although some assumptions must be made to reduce the data), but the frequency response of this type of system was thought to be considerably lower than the CCA system. Since a frequency response in excess of 400 KHz is needed to resolve the high–frequency spectral content of hypersonic boundary layers, this instrument had generally been ignored for high–speed flows. The approach used in this study, however, was to determine whether the frequency response of the easier–to–use CTA system could be optimized, so that a significant portion of the energy spectrum could be captured.

Customized hot–wire probes were built in an effort to reduce the probe impedance and thus increase the system frequency response. Copper–plated tungsten wire 2.5 μm in diameter was soft–soldered onto the probe prongs, and a 0.5 mm active length was etched using a sulfuric acid solution. The hot–wire frequency response was deduced using square–

wave injection, and a $-3\ dB$ point of 700 KHz was regularly achieved in the freestream of a Mach 10 helium pilot tunnel. The single normal wire was operated in a symmetric bridge at an overheat ratio, τ, of about one, so that, as a first estimate, stagnation temperature fluctuations could be neglected. In addition to the extraordinary frequency response, the absence of the "strain gauging" phenomenon and the survivability of the hot wires illustrate the potential applicability of CTA to hypersonic flows.

The Mach 10 pilot tunnel was also used to determine the recovery temperature of the unheated 2.5 μm wires, and to investigate the heat transfer relationship of the heated wires. The recovery factor, η, was found to be slightly greater than one, and is in agreement with other transitional and free–molecular flow data when end–conduction effects are considered. Despite the relatively high Knudsen number of the flow (Kn_0 as high as 5), a well–behaved and repeatable cooling law was found: $Nu_0 = Af(\tau) + Bg(\tau)Re_0^{0.73}$, where $f(\tau)$ and $g(\tau)$ were determined by calibrating at various overheat ratios, and A & B are constants which have a slight dependence on wire geometry. The attached figure shows the results of a typical calibration, achieved by varying the tunnel stagnation pressure from 900 *psi* to 100 *psi*. The subsonic continuum form of this cooling law, known as "King's Law", has a Reynolds number exponent of 0.5, and the free–molecular form correlates with $Re_0^{1.0}$. The wires used in this study are in the overlap region between continuum and free–moecular flow, and thus have a Reynolds number dependence somewhere between that of the two regimes.

The goal for the remainder of the summer is to obtain mass–flux fluctuation profiles across the transitional and turbulent boundary layers of the High–Reynolds–Number Mach 20 Helium Tunnel. The study will be done on a 4° wedge, with a flow Mach number of 10 behind the shock. The hot wires will be calibrated in the Mach 10 pilot tunnel, and the data reduced using the recovery factor and the cooling law found earlier. In the long term, this study will be followed by the development of dual–wire probes, crossed–wire probes, and a hybrid laser and hot–wire technique, all to be applied to the Mach 10 helium boundary layer. One type of dual normal–wire probe, with the wires separated by 0.5 mm and operated at two different overheat ratios, will be used to simultaneously determine both T_0' and u'. With such a probe, there is no need to resort to assumptions about the relative sensitivity of the CTA system to mass–flux and stagnation temperature, and the questionable Strong Reynolds Analogy is not needed to deduce u'. Dual normal–wire probes with a larger separation will be used to study the large–scale structure of the boundary layer, and the crossed–wire probe will allow measurement of the Reynolds shear stress, $u'v'$. The hybrid technique, employing single–point Rayleigh scattering and closely–spaced normal wires, will provide measurements of u', T_0', ρ', and p'. These would be the first measurements of fluctuating pressure within a boundary layer, and may be important in understanding hypersonic boundary layer physics.



Nusselt vs Wire Reynolds Number
RUN NURE23
η = 1.00
τ = 0.757
Nu_0
$Re_0^{0.73}$
c1=0.1579 c0=0.0083
error= 0.723
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0
1
2
3
4
5
6